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Original Investigation

The Impact of Training Load on Running Gait Variability: A Pilot Study

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Purpose: Running gait variability appears to be a new metric related to fatigue in long-distance runners. However, no study has verified the changes in gait variability over a longitudinal study involving well-experienced runners. Therefore, the aim of this study was to investigate the changes in gait variability in distance runner before and after a 9-week endurance training program.
Methods: A male runner (age 23 years; body mass 58 kg; stature 1.70 m, BMI 20 kg·m^{-2}) completed two critical speed (CS) test and six trial at different speeds (calculated by CS) with 9-week of training in-between. At the same time heart rate (HR) was continuously recorded and normalized as a percentage of the maximal heart rate (220 - age) %HR_{max}, serving as a proxy for metabolic expenditure. Additionally, kinematic (contact time (CT), flight time (FT), step length (SL), step rate (SR)) and kinetic measurements (leg (k_{vert}) and vertical (k_{leg}) stiffness), were recorded. While the running gait variability was calculated as phase coordination index (PCI).
Results: CS and HR were 16.40/18.00 km·h^{-1} and 93.19±1.23/93.81±2.38 %HR_{max} in baseline and after the training, respectively. The kinematic and kinetic variables studied at different speeds (13.80-14.40-15.00-15.70-16.40-17.10 km·h^{-1}) showed a significative training effect vs baseline conditions for CT (*P*= .010), FT (*P*= .010), SL (*P*= .002), SR (*P*= .002), k_{vert} (*P*= .003) k_{leg} (*P*= .0001) At the same way the metabolic demand and PCI changed significantly after the training compared to the baseline condition for average/maximum HR (*P*= .009 – 0.024, respectively) and PCI (*P*= .009).
Conclusions: These results suggest that gait variability is one mechanical determinant that demonstrates the adaptation of training load when neuromuscular output related to physiological efforts is under stress conditions, such as running training. Therefore, PCI could be a useful tool for monitoring the impact of running training load on bilateral running coordination.

Keywords: human locomotion; footstep pattern coordination; running performance; endurance runners.

Introduction

The dynamic nature of human movement has become an increasingly intriguing focus in the field of sports science. It provides valuable perspectives into the fundamental aspects of human locomotion, with a particular emphasis on bioenergetics and control. Numerous research endeavours have delved into exploring the variability inherent in different forms of bipedal human gait, including activities like pedaling,[1,2] walking,[3,4] race walking,[5–7] and running.[8–14] Despite their unique attributes, these footstep styles consistently demonstrate predictable movement patterns over time. The human bipedal gait is a complex undertaking that requires coordinated lower limb movements and the orchestration of physiological muscle responses to accommodate various environmental conditions, whether natural or otherwise.[15] Individuals must adjust their walking cycle to align with immediate environmental factors and attain desired target values.[16]
Recognizing the significance of variability in coordinating and controlling the sensorimotor system is crucial in motor control research. Deviations in variability, whether exceeding or falling short, during movement have been demonstrated to negatively impact motor task performance.[17,18] Accomplished athletes consistently demonstrate lower variability in kinetic and kinematics variables compared to less-skilled counterparts, underscoring the importance of variability in attaining superior performance.[19] Accomplished runners showcase diminished variability in critical variables like step length and frequency, directly enhancing running speed and reinforcing the importance of minimized outcome variability.[20]
Fatigue plays a pivotal role in shaping movement variability, with prolonged activity or muscle fatigue during training being linked to heightened variability.[21,22] This occurrence can be explained by the role of movement variability in adapting to environmental perturbations, thereby maintaining performance, as evidenced in studies on muscle fatigue during occupational tasks.[23] Despite the extensive examination of fatigue's impact on running,[24,25] the connection between movement variability, movement outcome, and how it adjusts in response to heightened fatigue during training remains largely unexplored.
Gaining insights into the constancy of variability and its fluctuations with increasing fatigue is essential to pinpoint the optimal time for assessing an athlete's typical variability during exercise. Variability values can shift within an exercise session, particularly as athletes encounter fatigue or adapt to the task's intensity. While prior research has concentrated on scrutinizing variability changes before and after fatiguing exercise,[26] there has been limited exploration of temporal changes during different

phases of an exercise period. Nevertheless, it remains unclear whether chronic fatigue, accumulated during periods of variable training load, affects motor control changes, and if so, whether these effects can be leveraged to discern the advantages of motor control. Consequently, this study aimed to examine alterations in gait variability before and after nine training weeks. Building on previous findings suggesting variability changes with fatigue, the hypothesis posited that variability would rise during a high-intensity continuous running training protocol.[27]

Methods

Participant

One male runner (age 23 years; body mass 58 kg; body height 1.70 m, BMI 20 $kg \cdot m^{-2}$) voluntarily participated in this study. Inclusion criteria were training volume of more than 60 km per week, engaging in more than 3 training sessions per week, having performed at least three running races on 10-km in the last six months. Furthermore, participant was required to be in good health without any neurological or musculoskeletal injuries. After being informed on the purpose and the procedures of the study, all the participant provided the written signed informed consent to participate in study that was approved by the local ethics committee and was performed in accordance with the principles of the latest version of the Declaration of Helsinki.

Experimental Design

Experimental design was performed on different phases, testing and training. Testing was carried over days, with a 7-days interval. On the first day, anthropometric measurements were taken and familiarisation on a track and field with a foot-pods. On the second/fourth day, after an individual tapering week[28] to avoid any fatigue effects, the participant took part in a Critical-Speed (CS) test.[29] On the third/fifth day the participant took part in a six 1000m trial at different speeds (calculated -/+ by CS) with a 5' passive recovery in-between. Before testing and training, participant was asked, to start after a 10-min warm-up at self-selected running speed.

Training was performed on 9-week at different training-intensity zones and mileage. The weekly load was fixed with 50 km, while the intensity-zones changed every three weeks (Table 1). Each training intensity session was fixed as Z2 (intensity equivalent to the critical speed), Z1 (-1 $km \cdot h^{-1}$ on Z2), Z3 (+1 $km \cdot h^{-1}$ on Z2). In the same weekly training for each training session the participant running at Z1-Z2-Z3. Thus, it was used Z1 training on constant running (Z1), while Z2 training was performed on 6.5/8/9 km (Week 1-3/4-6/7-9) for two training session per week. For example, in the first three weeks the training session (Z2) was organized with 4 trials (1× 500m + 3 × 2000m), in the next three weeks (Z2) was organized with 4 trials (4 × 2000m), while in the last three weeks (Z2) was organized with 4 trials (1× 1000m + 4 × 2000m). In-between trial on Z2 training sessions was fixed a 3' of the active recovery (running self-selected speed). Finally, on Z3 training intensity two training session per week was performed on different 500m trials with 3' of the passive recovery.

All procedures were performed on an official track and field 400m circuit at 0% incline (average temperature 22.5±4.3° C, and relative humidity of 19.2±2.2%) between 10:00 a.m. and 12:00 a.m., to ensure ecological validity. The participant wore running clothing and shoes (Mizuno Wave Prodigy, Osaka, Japan).

Instruments

Heart rate (HR) was continuously recorded during the trial (Polar H-10, Kempele, Finland), and it was normalized as a percentage of the maximal heart rate (220 - age) $\%HR_{max}$, serving as a proxy for metabolic expenditure. All training sessions was able to determinate the training load, wich quantified using training Impulse (TRIMP; duration in minutes multiplied by $\%HR_{max}$).[30] At the same time, a foot-pod RunScribe™ system (Scribe Lab. Inc. San Francisco CA, USA) with a sampling rate of 500 Hz (precision of .002 s) attached to the lace shoe of the right and left leg, recorded the footsteps data.[31] The foot-pod was calibrated before and re-checked after each trial. Results from RunScribe™ were taken from their website (https://dashboard.runscribe.com/runs) into the .csv file. Kinematic and kinetic parameters were recorded including contact time (CT, ms), flight time (FT, ms), step rate (SR, min), step length (SL, m), and stride time (ST, s) (calculated as the sum of CT (left and right) + FT (left and right)), as well as leg ($k_{leg,}$ $kN \cdot m^{-1}$) and vertical ($k_{vert,}$ $kN \cdot m^{-1}$) stiffness were calculated.[32] To analyse the bilateral coordination the phase coordination index (PCI) was calculated according to the Plotnik's eaquation.[15]

Table 1. Weekly training intensity zones

Period	Z1 (km)	Z2 (km)	Z3 (km)	Total (km)
Week 1-3	35.00	13.00	2.00	50.00
Week 4-6	30.00	16.00	4.00	50.00
Week 7-9	25.00	18.00	7.00	50.00

Note: Z2 (intensity equivalent to the critical speed), Z1 (-1 $km \cdot h^{-1}$ on Z2), Z3 (+1 $km \cdot h^{-1}$ on Z2).

We assessed left-right coordination in running gait using the PCI, following the method described by Plotnik and colleagues.[15] This index involved normalizing step time in relation to stride time. Step time refers to the time interval between a heel strike and the subsequent one of the contralateral leg, while stride time is the time interval between a heel strike and the consecutive one of the same leg. The normalization of step time with respect to stride time allowed us to calculate the phase (ϕi) of each stride, serving as an index of bilateral coordination.[15] To ensure consistency of participant, regardless of potential dominance differences, we calculated the average step time for both legs and used the leg with the longer step time as the reference for gait cycles. Subsequently, we computed ϕi values for the other leg using the formula:

$$\phi i = 360° \times \frac{t_{Si} - t_{Li}}{t_{L(i+1)} - t_{Li}} \qquad (1)$$

where t_{Si} and t_{Li} denote the time of the i-th heel strike of the legs with the short and long ST, respectively, and $t_{L(i+1)} > t_{Si} > t_{Si}$. The denominators in equation (1) correspond to the step time (ST) of the leg with the longest step time. Furthermore, we applied a conversion factor of 360 to transform the variable into degrees. A ϕ value of 180° signifies successful running symmetry, where step time constitutes half of the gait cycle for each step. The evaluation of the accuracy and consistency of phase generation is encompassed by running gait variability, serving as the primary outcome. To assess the accuracy level in phase generation, measuring how closely the series of generated phases align with the value 180°, we calculated the mean value of the absolute differences between the phase at each stride and 180°. This measure is denoted as ϕ_ABS:

ϕ_ABS [°]= $\overline{|\phi_i - 180°|}$.

To assess the level of consistency in phase generation across all strides for each participant, we calculated the coefficient of variation of the mean of ϕ, representing this consistency as ϕ_CV [%]. To account for the relationship between ϕ_ABS and ϕ_CV, we derived the phase coordination index (PCI) as follows: PCI = ϕ_CV + Pϕ_ABS, where Pϕ_ABS = 100 × (ϕ_ABS/180). Additional details regarding the association between ϕ_ABS and ϕ_CV can be found in the work by Plotnik and colleagues.[15] Notably, PCI provides insights into both the accuracy and consistency of phase generation.

Statistical analysis

Results are expressed as mean±standard deviation (SD). Shapiro-Wilk test was used to verify the assumption of normality of the distributions for each raw data. t-test was used to assess differences at the five speeds for HR, CT, FT, SL, SR, k_{vert}, k_{leg}, and PCI between before and after the training, respectively. The significance level was fixed $P \leq .05$ using Statistical Package for Social Science software (Version 28.0, IBM SPSS Statistics, Chicago, IL, USA).

Results

The critical speed (CS) in baseline was 16.40 km·h^{-1} with a PCI of 2.93% and HR 93.19±1.23 %HR$_{max}$, while after 9 weeks the CS was 18.00 km·h^{-1} with a better PCI of 2.83% and HR 93.81±2.38 %HR$_{max}$. The kinematic and kinetic variables studied (Table 2) at different speeds (13.80, 14.40, 15.00, 15.70, 16.40, 17.10 km·h^{-1}) showed a significative training effect when compared vs baseline conditions for CT (P= .010), FT (P= .010), SL (P= .002), SR (P= .002), k_{vert} (P= .003), k_{leg} (P= .0001). At the same way the metabolic demand and PCI changed significantly after the training (Figure 1) compared to the baseline condition for average/maximum HR (P= .009 – 0.024, respectively) and PCI (P= .009). Training load (Figure 2) per week were 14,128 - 11,764 - 16,525 - 16,444 - 16,367 - 16,459 - 21,102 - 12,642 - 19,317 TRIMP from the first to the last week, respectively.

Discussion

The purpose of this study was to investigate the impact of the training load on changes in gait variability in distance runner before and after a 9-week endurance training program. Our hypothesis was supported by our study findings, which demonstrated that running gait variability were reduced (improved) when the training protocol caused an improved performance. In our study the training load was 3661±1207 TRIMP (Figure 2) for nine weeks calculated on a total of 450 km performed by the runner. This load was able to overcome the potential effects relate to the overreaching when the training load was 5000 TRIMP on seven days as demonstrated by Fuller et al..[27] In fact, physiological and kinetic/kinematic variables improved after nine training weeks.

From physiological point of view, also if the there was a physiological stress related to the training load (Figure 2), nine-weeks was able to determinate a physiological adaptation if considering a decreased of HR (6.28±2.46 %HR$_{max,}$ Figure 1) in six speeds considered (13.80 – 17.10 km·h^{-1}). At the same way the critical speed which represent the maximal physiological steady state was improved by 16.40 to 18.00 km·h^{-1}. The findings in our study align with the outcomes of numerous training studies that utilized various training methods over an 8-week period with recreational runners. In a recent study conducted by Pugliese et al.,[33] a notable enhancement in 5 km performance, approximately 3%, was observed.

Table 2. Kinematic and kinetic variables at different speeds before and after the training

Variables	Time	13.80 km·h^{-1}	14.40 km·h^{-1}	15.00 km·h^{-1}	15.70 km·h^{-1}	16.40 km·h^{-1}	17.10 km·h^{-1}
CT (ms)	Before Tr	214±7.57	211±6.52	206±7.29	201±6.81	197±7.35	211±8.67
	After Tr	208±4.35	198±5.81	194±6.56	193±6.19	186±6.90	182±7.79
FT (ms)	Before Tr	124±11.77	127±12.45	127±10.62	127±11.17	123±10.00	112±17.77
	After Tr	125±10.26	133±9.63	132±9.25	133±9.77	130±10.51	127±13.55
SL (m)	Before Tr	1.49±0.09	1.53±0.07	1.55±0.07	1.56±0.07	1.56±0.10	1.44±0.16
	After Tr	1.33±0.10	1.39±0.05	1.39±0.05	1.41±0.08	1.43±0.07	1.42±0.09
SR (min)	Before Tr	178±4.33	178±5.08	181±4.31	182±4.99	187±3.90	186±5.97
	After Tr	181±8.31	181±4.04	184±3.73	184±3.72	190±4.71	195±5.10
k_{vert} (kN·m^{-1})	Before Tr	20.07±0.90	20.47±0.83	21.33±1.03	21.99±1.06	23.07±1.13	22.08±1.98
	After Tr	21.83±2.75	22.48±0.89	23.30±1.08	23.45±0.98	25.12±1.27	26.42±1.88
k_{leg} (kN·m^{-1})	Before Tr	8.52±0.71	8.58±0.69	8.71±0.70	8.90±0.76	9.06±0.74	8.87±0.91
	After Tr	11.89±0.58	10.92±0.76	11.20±0.82	11.12±0.88‡	11.45±0.92	11.83±1.13

All data are expressed as mean ± standard deviation

At the same time, based on the kinematic and kinetic data, we observe an increased stiffness (k_{vert} and k_{leg}) which leads to a decreased CT and increased FT-SL-SR in all six monitored speeds. These kinematic and kinetic results support the notion that the daily training load proposed in this study was effective in enhancing the metabolic demand (Figure 1) across all six speeds relative to the critical speed.

Nevertheless, as far as we are aware, this study represents the initial attempt to explore the impact of extended exposure to fatigue on motor control during a running task. The discovery of efficient, noninvasive metrics linked to fatigue accumulation

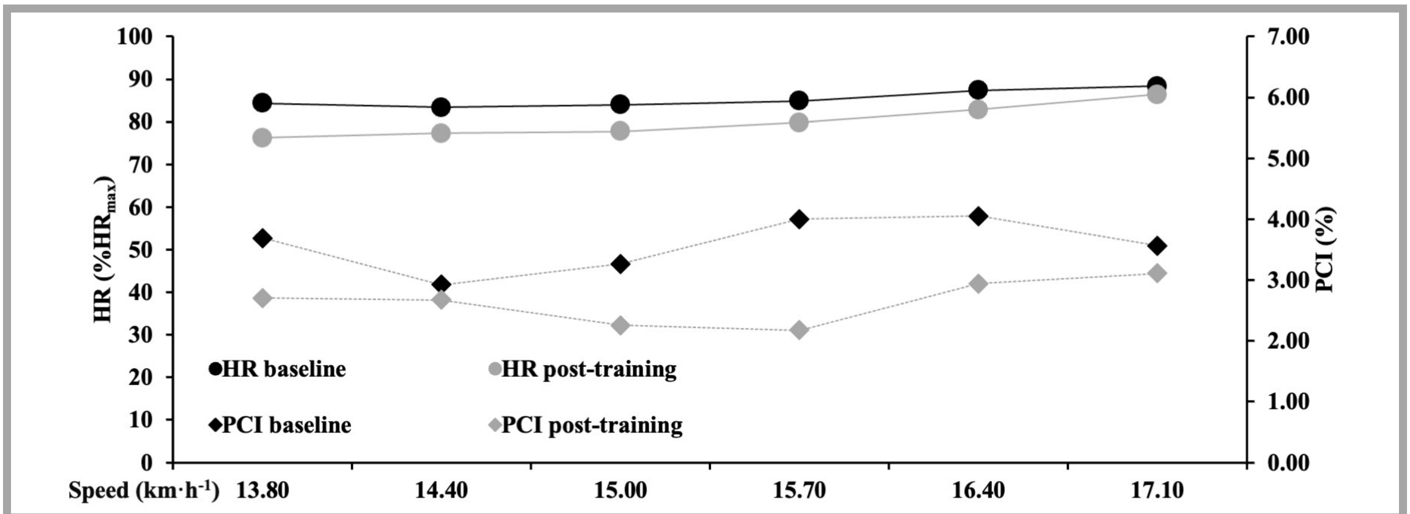

Figure 1. Hear Rate (HR) and phase coordination index (PCI) at different speeds before and after the training.

holds significance in preventing nonfunctional overreaching. By integrating basic motor control assessments with established physiological and psychological indicators of overreaching, we can establish a more holistic evaluation procedure for gauging athletes' capacity to withstand intense training regimens. Fatigue is a multifaceted phenomenon that results from intricate interactions between central and peripheral factors.[34] The evaluation of gait variability when exposed to fatigue offers a pathway to delve into the role of central mechanisms, as stride-interval correlation characteristics are responsive to central, rather than peripheral, alterations.[35] Previous research has illustrated diminished stride-interval long-range correlations during exhaustive running, implying that compromised motor control at more "advanced" brain centers could be a contributing factor to the onset of fatigue.[21] In our study, the training protocol led to enhancements in running gait variability.

Hence, gait variability may serve as a highly sensitive biological signal for detecting functional overreaching, with potential implications for injury prevention.[27] Additionally, existing evidence suggests that stride variability could be a predictive factor for injuries in runners.[21,36] Nevertheless, as far as our current knowledge goes, the joint analysis of these two factors to assess their combined potential in predicting injury risk remains unexplored.

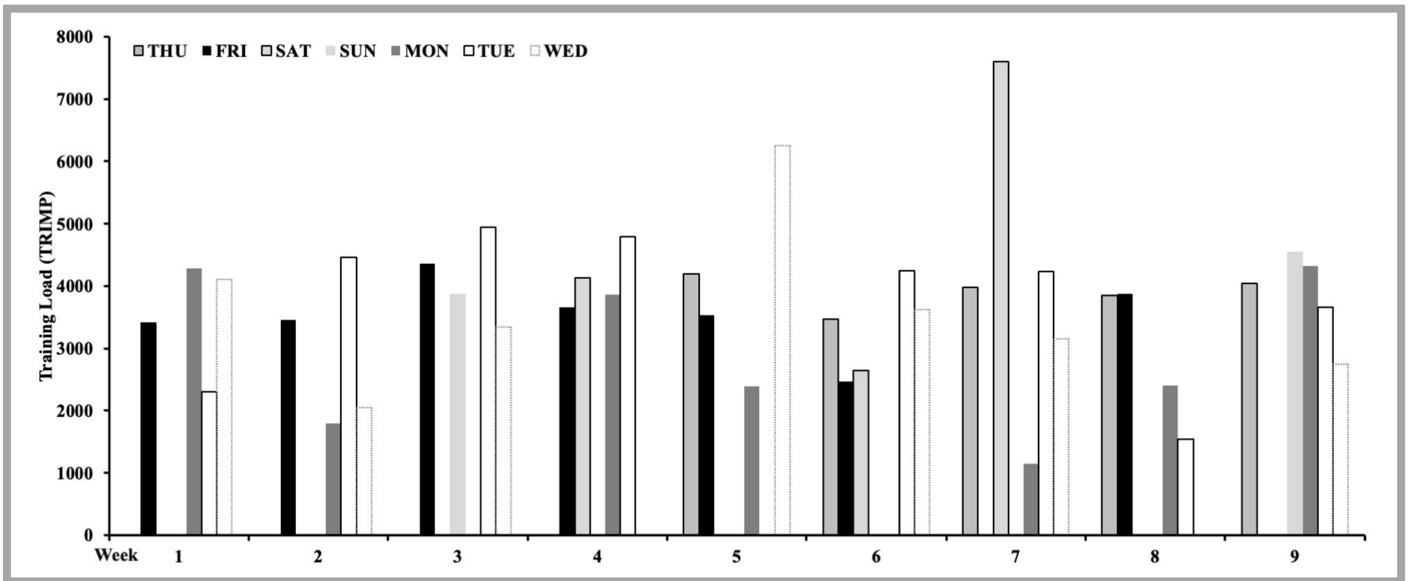

Figure 2. Traning Load for 9-week.

Practical Applications

The fluctuations in PCI observed throughout the training program corresponded to performance shifts resulting from high-intensity training. This suggests that PCI properties have the potential to serve as a valuable indicator for discerning training responses, identifying functional overreaching, and potentially mitigating the risk of nonfunctional overreaching. While we employed fixed running speeds to measure participants' stride intervals for the sake of practicality and applicability to real-world sporting scenarios, it is worth considering that tracking changes in PCI may exhibit a stronger connection with performance alterations when assessed using individually tailored running speeds aligned with each athlete's preferred pace.

Conclusions

The intensity of training has the potential to impact the regulation of running gait, potentially through its effects on motor control in more advanced brain centers. The assessment of PCI offers a valuable means to monitor an athlete's capacity to withstand high training loads, facilitating the identification of both functional and non-functional overreaching. Subsequent research endeavours should explore the sensitivity of PCI measurements at various speeds, allowing for comparisons across different training intensities.

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Ethical Committee approval

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Informed Consent Statement

Informed consent was obtained from one participant involved in this study.

Topic

Sport Science.

Conflicts of interest

The authors have no conflicts of interest to declare.

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Declaration if used ChatGPT

We don't used ChatGPT.

Author-s contribution

Conceptualization, J.P. and G.M.; methodology, J.P. and F.E.; software, J.P.; validation, J.P. and G.M.; formal analysis, J.P. and F.E.; investigation, J.P.; resources, J.P. and F.E.; data curation, J.P. and G.M.; writing—original draft preparation, J.P.; writing—review and editing, J.P.; visualization, J.P. and G.M.; supervision, J.P. and F.E.; project administration, J.P.. All authors have read and agreed to the published version of the manuscript.

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